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Technical Report ARWSB-TR-17011

THE COMBINED EFFECTS OF STRESS CONCENTRATION AND TENSILE STRESSES FROM AUTOFRETTAGE ON THE LIFE OF PRESSURE VESSELS

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February 2017

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Weapons Software & Engineering Center
Benét Laboratories
Watervliet, NY 12189

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
Feb 2017

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
THE COMBINED EFFECTS OF STRESS CONCENTRATION AND TENSILE STRESSES FROM AUTOFRETTAGE ON THE LIFE OF PRESSURE VESSELS

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
E. Troiano
G.N. Vigilante
L.B. Smith
J.H. Izzo

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, RDAR-WSB
Watervliet, NY 12189-4000

8. PERFORMING ORGANIZATION REPORT NUMBER
ARWSB-TR-17011

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Thick walled pressure vessels are often hydraulically or mechanically overstrained in order to impart favorable near bore residual compressive hoop stresses in an attempt to enhance fatigue life. As a result of imparting these favorable near bore compressive stresses, self-compensating tensile residual stresses result, which in some case can be detrimental. In the early stages of development of each system, multiple full size vessels are hydraulically fatigue tested and a safe life is determined. Recent developments have pushed these vessels into longer years of service. In some cases, this has caused unanticipated field issues and resulted in field service lives that are less than the original safe lives. These service issues have several common threads which link them together including; tensile residual stresses from autofrettage, outside diameter stress concentration effects including features designed into the vessel as well as unanticipated effects from inadequate material quality, and long term effects from corrosion and pitting. This paper will present several case studies which will identify the cause of the reduced lives and propose corrective action.

15. SUBJECT TERMS
Thick Walled Pressure Vessels; Autofrettage; Cracking; Residual Stresses; Fatigue Testing; Corrosion; Pitting

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	U/U	U	U/U	8	E. Troiano

19b. TELEPONE NUMBER (*Include area code*)
(518) 266-5112

INSTRUCTIONS FOR COMPLETING SF 298

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9. SPONSORING/MONITORS AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Thick walled pressure vessels are often times hydraulically or mechanically overstrained in order to impart favorable near bore residual compressive hoop stresses in an attempt to enhance fatigue life. As a result of imparting these favorable near bore compressive stresses, self-compensating tensile residual stresses result, which in some case can be detrimental. In the early stages of development of each system, multiple full size vessels are hydraulically fatigue tested and a safe life is determined by assuming a log normal distribution at the 90% lower confidence bound on the 0.1th percentile of the population.

Recent developments have pushed these vessels into longer years of service than originally anticipated. The extended service time has in some cases caused unanticipated field issues and resulted in field service lives that are less than the original safe lives previously established. These service issues have several common threads which link them together including; tensile residual stresses from autofrettage, outside diameter stress concentration effects including features designed into the vessel as well as unanticipated effects from inadequate material quality, and long term effects from corrosion and pitting This paper will present several case studies which will identify the cause of the reduced lives and propose corrective action.

MILITARY PROSPECTIVE AND EVOLUTION OF THE AUTOFRETTAGE PROCESS

Autofrettage of thick walled pressure vessels of the type used in manufacture of artillery and tank columbiads, as well as in thick walled piping and tubing is not a new process. While the concept of autofrettage is not a new one, the method of applying the autofrettage has gone through an evolutionary process. Currently utilized methods for autofrettage include single cycle hydraulic pressurization as well as mechanical wedge insertion. The process of autofrettage results in compressive bore hoop stresses which can significantly increase fatigue life and enhance safe operational pressurization. At the expense of applying these favorable compressive hoop stresses near bore, are the not so favorable self-compensating tensile hoop stresses near the outside diameter of the vessel.

A historical military prospective of autofrettage includes mentioning Thomas J. Rodman who obtained United States Patent No. 5236 on August 14, 1847 [1] for Improvement in Casting Ordnance. The patent provides instruction for "cooling guns and other heavy hollow castings" by inserting a cooling barrel into the bore which allows for solidification of a molten tubular casting from the bore to the outside diameter. Rodman was cooling from the bore in order to prevent thermal cracking that often resulted in castings of this size which were customarily cooled from the outside. In the patent, Rodman identifies four manufacturing issues which the patent is intended to correct, but unknown to Rodman at the time, he actually corrected five issues. The fifth being the generation of thermal residual compressive near bore hoop stresses in which this type of cooling imparts. Simply put, Rodman's patent resulted in thermal autofrettage.

Further experimentation by Wade in 1851 clearly showed an increase in performance and life of 8 inch and 10 inch columbiads manufactured with the Rodman technique verses columbiads manufacture by the traditional solid casting technique. Based on what was perceived to be promising fatigue results, Wade speculated "The great difference of endurance must therefore be ascribed, to the different methods by which the castings were cooled; and to them alone." The method, as Wade and Rodman would explain … "allowed the gun to contract upon itself while cooling, thus changing the way the metal reacted to the stress of firing."[2]

In a 1880s Report of the Ordnance Board, Lieutenant Coronels. S. Chrispin and T.G. Baylor and Major. C. Comly [3] using Rodman's process for building sea cost columbiads noticed that when they removed a disk from a casting made with the Rodman process and performed a slit test by machining a groove into the disk, the disk "springs open". They concluded that this "initial strain" was due to compressive near bore strains and went on to explain the benefits of this locked in strain. This test as described here and presented by Timoshenko and Goodier [4] approximately 80 years later is largely the same test used today to measure the amount of locked in residual hoop stresses imparted from current autofrettage techniques.

In 1910 L.B. Turner [7] provided a methodology for using hydrostatic pressure in order to accomplish the same compressive residual near bore hoop stress field that Rodman did. His methodology replaced the wire wrapping and shrink fitting processes that were available and commonly used at the time. The method was implemented in the United States in the 1930s to 1940s in thick walled pressure vessels and used extensively until approximately 1945 at which time it was largely abandoned. The abandonment had nothing to do with the process being inadequate, but in advancements in cleaner and higher strength materials and the inability to generate the needed pressures in order to autofrettage them. This hurdle was quickly overcome as they saw the benefit for both better materials and higher hydraulic autofrettage pressures.

It was in the 1960s that Tom Davidson, Dave Kendall, and Al Reiner working for the United States Army along with Don Newhall of Harwood Engineering implemented the use of a sliding wedge mechanical autofrettage. Autofrettage by the hydraulic "technique is, for all practical purposes, limited to pressures not exceeding 200,000 psi. To extend the use of autofrettage to higher pressure applications and to eliminate the many problems encountered in the use of pressures in the

range of 150,000 to 200,000 psi on a production basis, a new autofrettage process was developed. This new technique uses the mechanical advantage of a wedge to produce the desired bore enlargement, thus drastically reducing the pressure requirements to obtain a given amount of overstrain. This process, which is termed the swaging method of autofrettage, consists basically of passing an oversized swaging tool or mandrel through the bore of the cylinder to produce the desired permanent enlargement. The force required to move the mandrel may be provided by direct hydraulic pressure applied behind the mandrel or by a mechanical loading device." [6, 7]

AUTOFRETTAGE – THE GOOD AND THE BAD

As can be seen from the previous section, the evolutionary process of autofrettage was clearly driven by the influence of compressive near bore hoop stresses which positively and directly impacted both the elastic strength and the fatigue life of pressure vessels. However as a result of the process there must be an equal amount of stored tensile hoop stresses to balance the compressive hoop stress and therefore satisfy equilibrium. The tensile hoop stresses if properly managed will have minimal or no impact on the operation or safety of the vessel. There are times, and for various reasons, when the effects of these tensile stresses become a major contributor to the safety and longevity of these vessels. The next section will describe several case studies which explain how these tensile residual stresses from autofrettage have impacted the daily use of pressure vessels.

CASE STUDY 1 – CRACKING IN VESSELS WITH THRU HOLES [8]

Full size fatigue testing is required on all new developmental pressure vessels in order to establish a safe fatigue life. The method involves hydraulic fatigue cycling at the maximum operational pressure a minimum sample quantity of six full size vessels. This type of test has been verified to replicate field service conditions in thick walled pressure vessels [9]. Safe fatigue life is then determined by assuming a log normal distribution at the 90% lower confidence bound on the 0.1th percentile of the population. In this case study a region of the pressure vessel with through wall angled and circular holes (shown in the sketch in Figure 1) which are utilized to vent internal gasses and perform external work, was examined

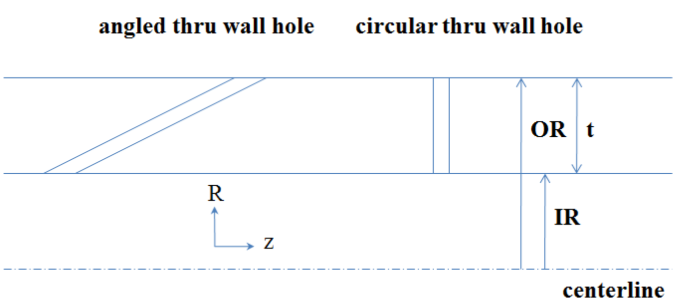

Figure 1 – Configuration of thru wall holes.

This particular region of the pressure vessel had been mechanically autofrettaged to 100% overstrain. The stresses in the angled thru wall holes of the vessel are shown as a function of wall location in Figure 2 and include the autofrettage residual hoop stress field $\sigma_{residual}$, which when coupled with the applied Lame pressure induced stresses (σ_{Lame}) and the stress concentration effects (K_t) associated with the angled thru wall hole induced an effective tensile stress (σ_{eff}) which exceeded the materials yield strength from approximately 40% of the wall thickness to the outside diameter of the vessel.

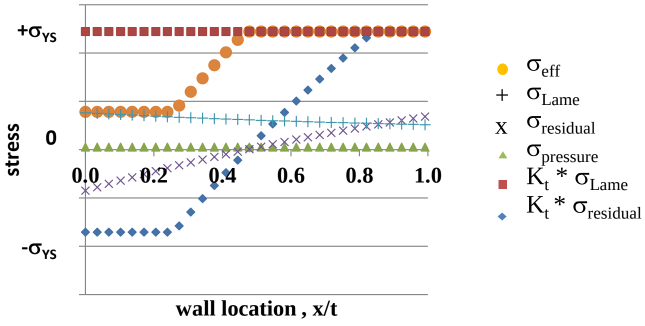

Figure 2 – Stresses present in angled thru wall hole.

These tensile stresses coupled with the hydrogen rich gaseous medium within the vessel as well as additional stress concentration effects from the long term general corrosion within the thru wall hole results in environmental cracking which initiate at the hole surface as shown in Figure 3.

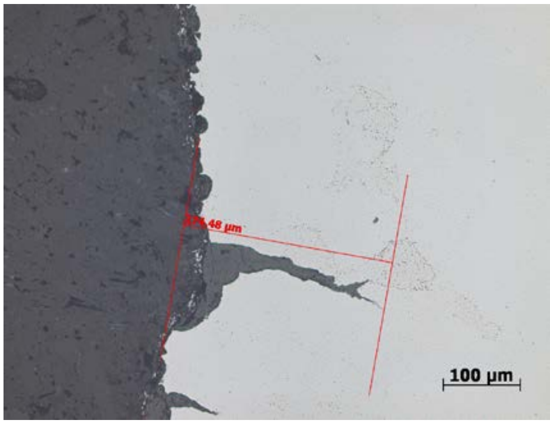

Figure 3 – Environmental cracking observed in angled thru wall hole.

These environmental, stress corrosion cracks, were then mechanically propagated during laboratory fatigue cycling until loss of pressure occurred. The final cracks are seen in Figure 4. Note the location of the fatigue crack in Figure 4, which clearly shows the beneficial effect of the near bore compressive hoop stresses from autofrettage and the minimal fatigue and environmental cracking nearer the bore. The process include pits formation as a result of general corrosion which sets up an electrochemical cell. The byproduct of the cell is the evolution of a small amount of hydrogen gas which coupled with the highly susceptible, high strength Cr-Mo-V steel (1200 MPa)

and the tensile residual stress field from autofrettage results in a pop-in of a small environmental crack. The cell then dies and no additional hydrogen is generated to further propagate the crack. Follow on corrosion then engulfs the existing crack and the process starts all over again.

Although it was shown that this region of the pressure vessel was not the life limiting fatigue region, several corrective actions were implemented in order to improve the thru wall hole life which included an improved and increased maintenance schedule to minimize general corrosion, thereby reducing the formation of the stress corrosion crack initiation sites. Also, an investigation was undertaken to apply a localized autofrettage to each independent hole in order to produce a local compressive stress field within the hole and completely eliminating any possibility of environmental crack initiation.

Figure 4 – Cross section of angled thru wall hole showing location of fatigue damage.

CASE STUDY 2 – ENVIRONMENTAL CRACKING IN AN EXTERNAL KEYWAY [10]

In August 1990 and unanticipated failure of a pressure vessel occurred during the final stages of production of a pressure vessel when a 1.7m long through wall crack grew from an outside diameter keyway as sh schematically in Figure 5. As is common of pressure vessels of this type, which are filled with aggressive hydrogen gas during their lifetime, a passive chromium barrier coating is applied to the bore of the vessel in order to prolong service life and minimize the effects from exposure to these gases. However the process of applying the chromium coating is in and of itself very aggressive in that it exposes the underling high strength, highly susceptible Cr-Mo-V steel to concentrated sulfuric and phosphoric acids, at elevated temperatures, during its application. Because the chrome depositions were uneven on this particular vessel, it was subjected to a sodium hydroxide stripping bath in order to remove the uneven chrome and prepare it for a second chrome plating. After uneven chrome was observed after the second application it was once again exposed to a second sodium hydroxide stripping operation. It was subsequent to this second stripping operation that the cracking was observed.

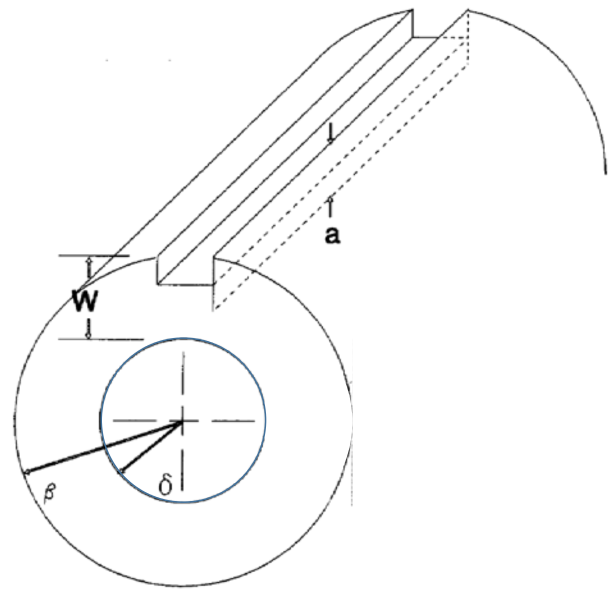

Figure 5 – Schematic of through wall cracking in an OD keyway during production of a thick walled pressure vessel.

This vessel prior to plating had been 100% overstrained in this region with an estimated hoop tensile residual stress on the outside diameter of the vessel of +578 MPa. The keyway configuration was such that the K_t was approximate 6.0, which resulted in the effective residual tensile stress in the root of the key way well above the 1200 MPa material yield strength.

Forensics examination of the fracture surface revealed two distinct region of corrosion covered intergranular crack extension believed to be the result of each Cr plating and stripping operation, followed by a third region with minimal corrosion, believed to be the final rapid crack advancement.

The mechanism of the unanticipated failure was the absorption of bulk hydrogen during exposure to the acid environments, migrating from the bore to the outside surface during the various plating operations, coupled with the localized tensile residual stress field from the autofrettage process in the keyway. It was speculated the thermal shock from subjecting to the room temperature pressure vessel to the elevated plating bath temperatures was significant enough to break any formation of protective oxide film at the outer surface thereby allowing fresh clean material to be continually exposed to aggressive hydrogen. Also, the process of application of Cr plating takes a considerable length of time. This exposure time is typically controlled in order to minimize any detrimental effect of bulk hydrogen absorption. Subsequent to proper plating, pressure vessels go through a low temperature thermal heating process to allow the minimal amounts of hydrogen trapped within the steel to escape. In this case no thermal processes were undertaken and as a result the hydrogen was allowed ample time to seek out the susceptible tensile residual stress field in the keyway.

Corrective recommendations made were to include a low temperature thermal bake out process subsequent to all Cr

plating operations, including those that need to be stripped for any reason. Also configurational changes were made in order to reduce the stress concentration effects of the keyway from K_t=6.0 to K_t =2.1, thereby reducing the effective stresses in the root of the key way by 3 times.

CASE STUDY 3 - CRACKING OF A PRESSURE VESSEL DURING AUTOFRETTAGE [11]

During mechanical swage autofrettage of a thick walled pressure vessel, a through wall crack developed and extended approximately 3.7m down the length of the pressure vessel as seen highlighted by the arrow in Figure 6. This pressure vessel configuration was in full production with literally hundreds being produced over the course of a year's time with no others vessels exhibiting this type of cracking. Another puzzling anomaly was that the crack did not follow any known outer diameter geometric stress concentrations as in the prior case study. The yield strength of the material was 1170 MPa and the overstrain designed into this section of the pressure vessel was approximately 50%, which would have resulted in a tensile outside diameter residual hoop stress of only +200 MPa.

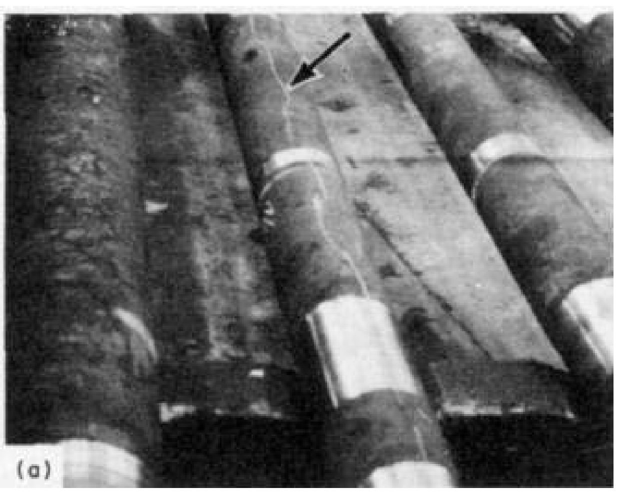

Figure 6 – 3.7m long though wall crack in pressure vessel.

Processing records revealed that the vessel had the received appropriate heat treatment and met all chemical, mechanical, metallurgical and manufacturing requirements.

Forensic visual metallographic and fractographic examination revealed a discolored network of non-metallic matter at what was believed to be the origin of the cracking. Further investigation with scanning electron microscopy shown in Figure 7 and highlighted by the arrow revealed that the area was rich in iron oxides. Iron oxide of this type are extremely rare in materials that have been vacuum degassed, as this forging had.

Normal processing of these vessels includes high temperature rotary forging from a right circular cylinder preform to near net shape final forging. It was speculated that this process resulted in a forging lap which trapped iron oxide scale below the surface during the forging operation. Subsequent rough machining of the outside surface prior to autofrettage simply masked the defect and rendered it undetectable both visually and with the commonly used magnetic particle inspection. During the swaging process, when the material is subjected to the maximum applied strain the pressure vessel simply started to unzip from the outside diameter towards the inside diameter and as the mandrel passed longitudinally down the length of the vessel the crack simply followed.

Since this type of failure is extremely unlikely, and impossible to predict since forging laps randomly occur during the rotary forging process no corrective action was implemented.

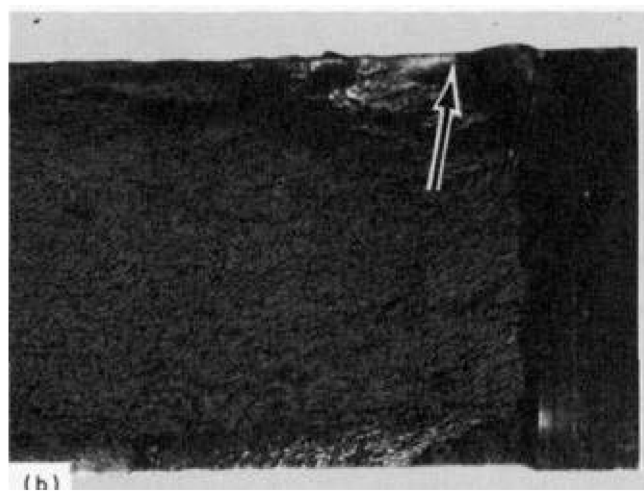

Figure 7 – SEM indicating non-metallic matter at origin of failure**.**

CASE STUDY 4 – ABUSIVE MACHINING IN AN EXTERNAL KEYWAY

In an unpublished report from 1993 a system under development was being tested when an earlier than anticipated fatigue failure occurred on the last pressure vessels being tested. The average life of the population tested before this failure was greater than 10000 cycles with a coefficient of variation of 12%, which from prior experience on similar vessels was anticipated. The subject vessel failed after only 5500 cycles from an external double keyway feature shown in Figure 8. Mechanical and chemical property testing as well as heat treatment inspection records verified that all vessels in test met or exceeded the requirements as set forth by the designers and therefore could not explain the outlier. Residual stress as measured by previously mentioned standardized slitting tests indicated that all vessels used in testing were properly mechanically autofrettaged with overstrains measured at 60% to 70% which results in a tensile residual outside diameter hoop stress of +230MPa. Follow-on metallurgical investigation revealed that a white layer was present in the root of the keyway that was approximately 0.05mm in depth. The white layer shown in Figure 9, which is believed to be a residual effect of aggressive machining operations which locally heated the adjacent material and produces untempered martensite, whereas the base metal, from Figure 9, is clearly tempered martensite. Since no heat treatment operations follow the machining of the keyway the

white untempered martensite remained with the vessel and because of its high hardness results in rapid crack initiation and poor localized fracture toughness. Also discovered during the dimensional inspection was that the root radius of the keyway, which was specified on the drawing was actually 0.3mm less than the minimum acceptable radius. Analysis from the dimensional investigation suggested that the stress concentration factor in this tight root radius to be approximately 3.7. This sharp stress concentration coupled with the +230 MPa tensile residual hoop stress from autofrettage at this wall location results in an effective residual tensile stress in the root of the keyway of over +861MPa.

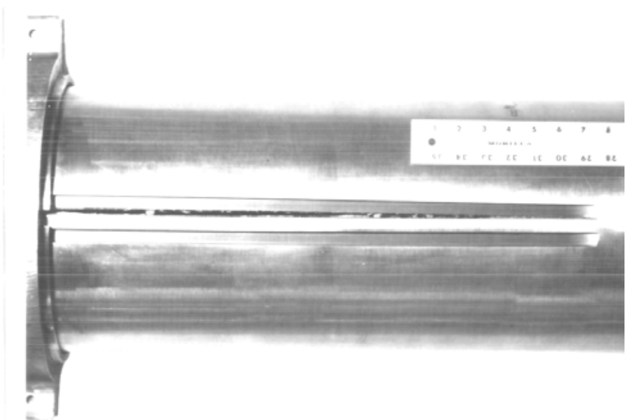

Figure 8 – Cracking in an external double keyway during laboratory fatigue testing.

The conclusion drawn from the investigation identified that the underlying cause of the failure to be the heat affected zone in the keyway as a result of increased mean stress effects due to autofrettage residual stresses. Not directly mentioned in the report but worthy of noting as a significant contributor in the failure was the sharp stress concentrator in the keyway which resulted in higher localized tensile hoop stresses than the previous vessels tested. Corrective actions included improved machining practices and better quality control in order to eliminate these effects.

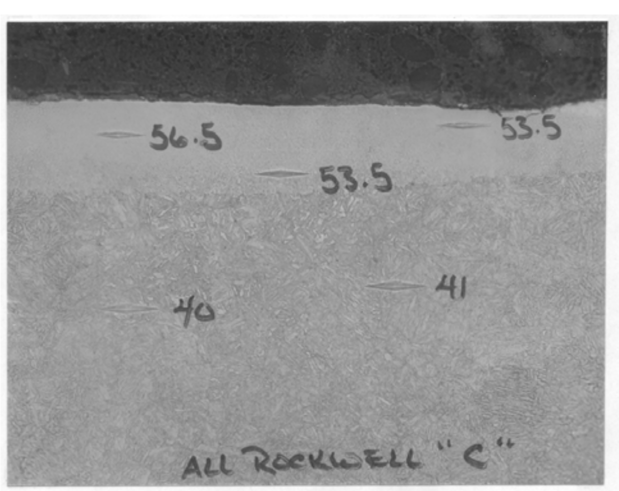

Figure 9 - White Layer and Hardness in keyway.

SUMMARY

Autofrettage, whether performed by thermal shrink fit, hydraulic over pressurization or the modern wedge insertion, results in advantageous near bore compressive hoop stresses that enhance both the elastic strength pressure of the vessel and improve overall fatigue resistance. However the process also results in an outside diameter self-compensating tensile residual stress field. This resulting residual stress field, if properly managed, can result in minimal or no detrimental effects on the processing or life of the vessel.

In each of the case studies presented the combination of tensile applied and residual outside diameter hoop stresses coupled with both anticipated as well as unanticipated stress concentration effects, both geometric and microstructural were responsible for each of these failures. Proper management of the combination of these stresses and stress concentration effects is imperative for proper operation and a long service life.

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